Axion Inflation and the Weak Gravity Conjecture

Gary Shiu

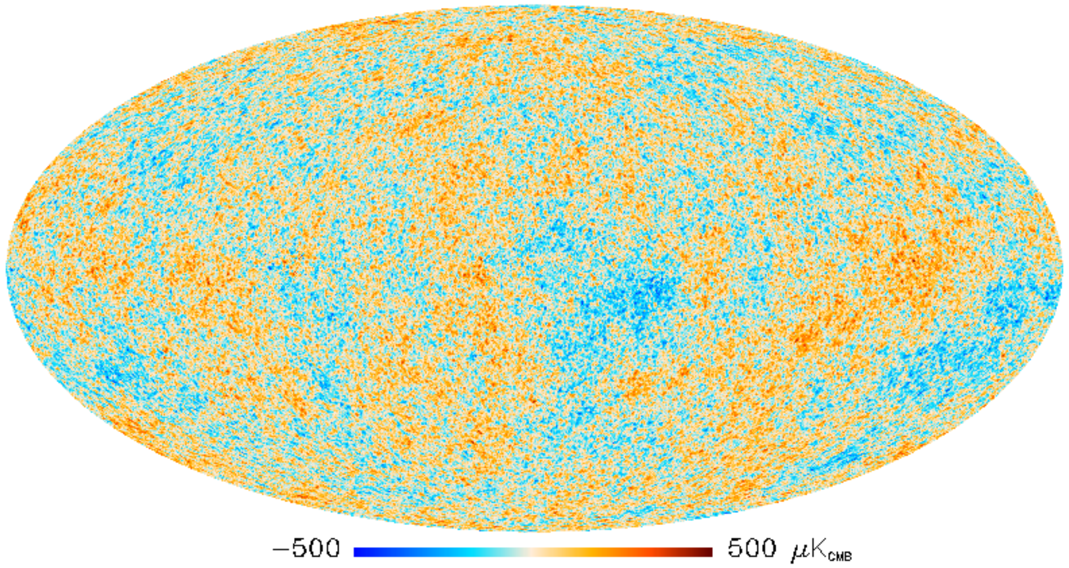
J. Brown, W. Cottrell, GS, P. Soler: 1503.04783, 1504.00659

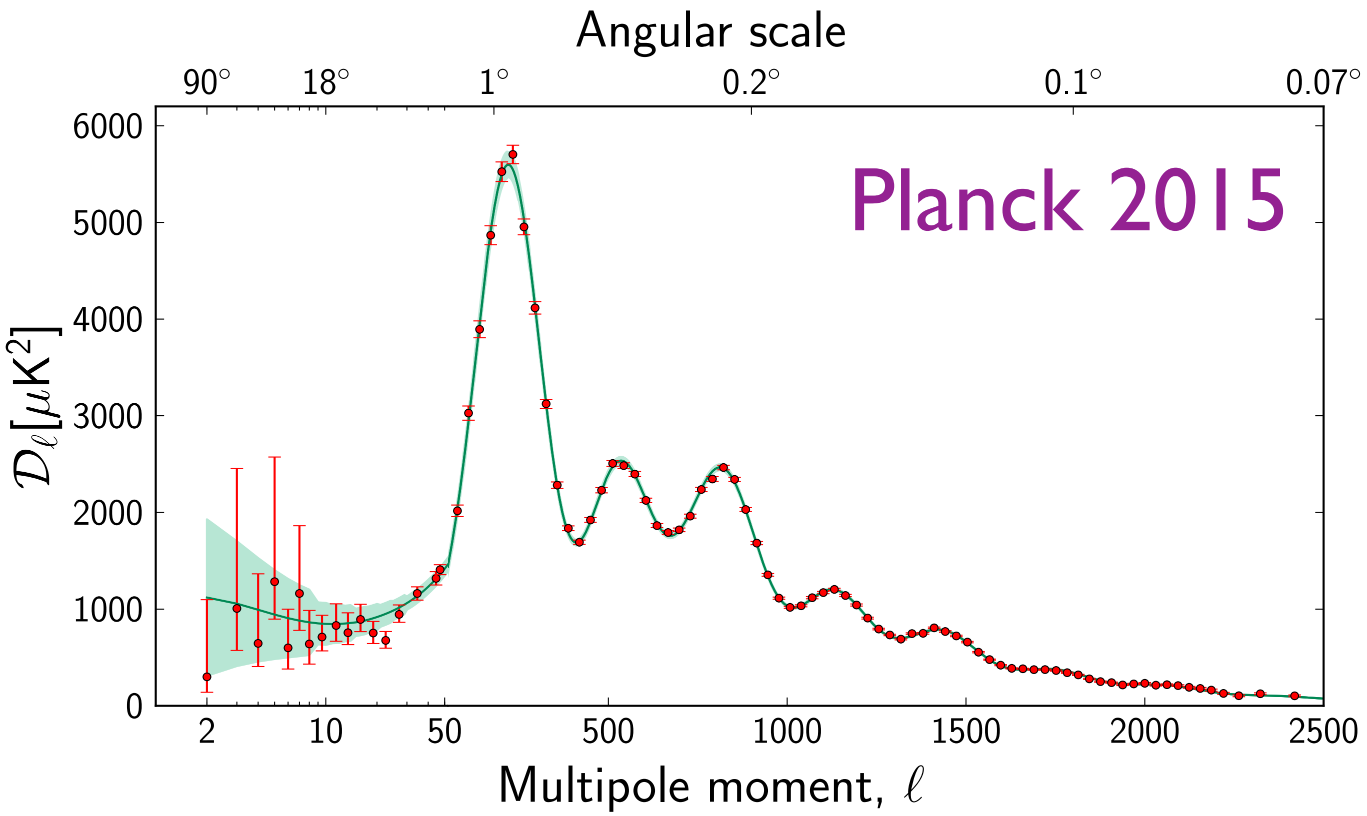
KIAS-YITP Joint Workshop 2015: Geometry in Gauge Theory and String Theory

Inflationary Universe

Starobinsky; Guth; Linde; Albrecht, Steinhardt; …

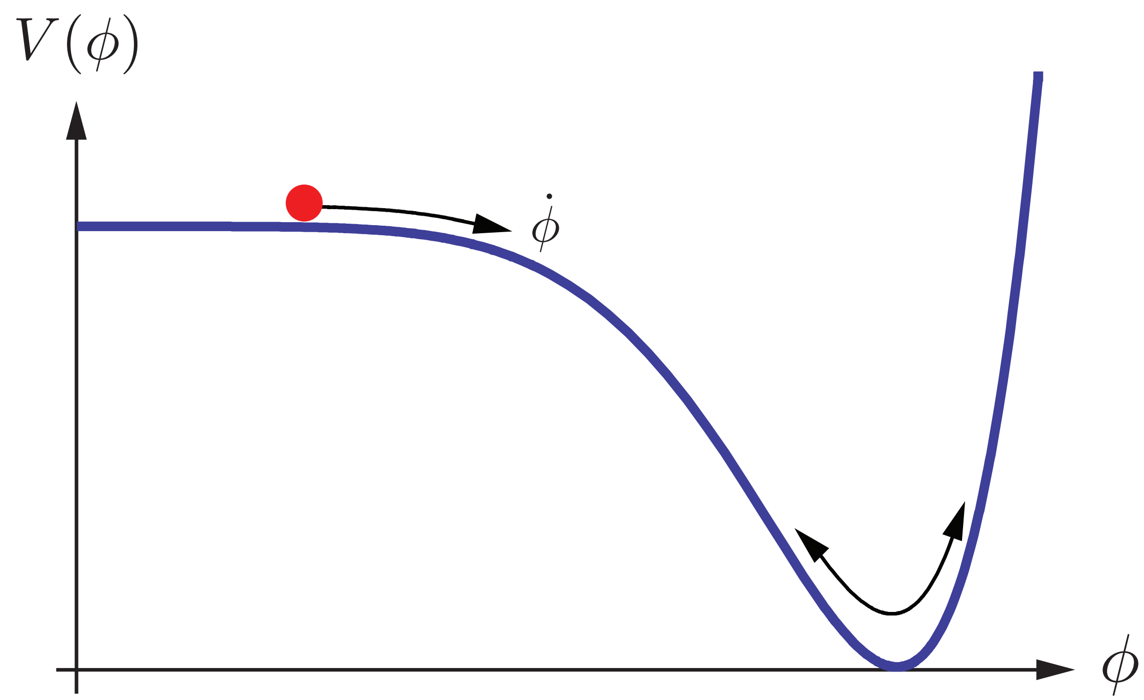
- Solves the flatness and horizon problems.





- An almost scale-invariant, adiabatic, Gaussian primordial spectrum predicted by inflation in good agreement with data.

UV Sensitivity of Inflation



$$\epsilon = \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 << 1$$

$$\eta = M_P^2 \frac{V''}{V} << 1$$

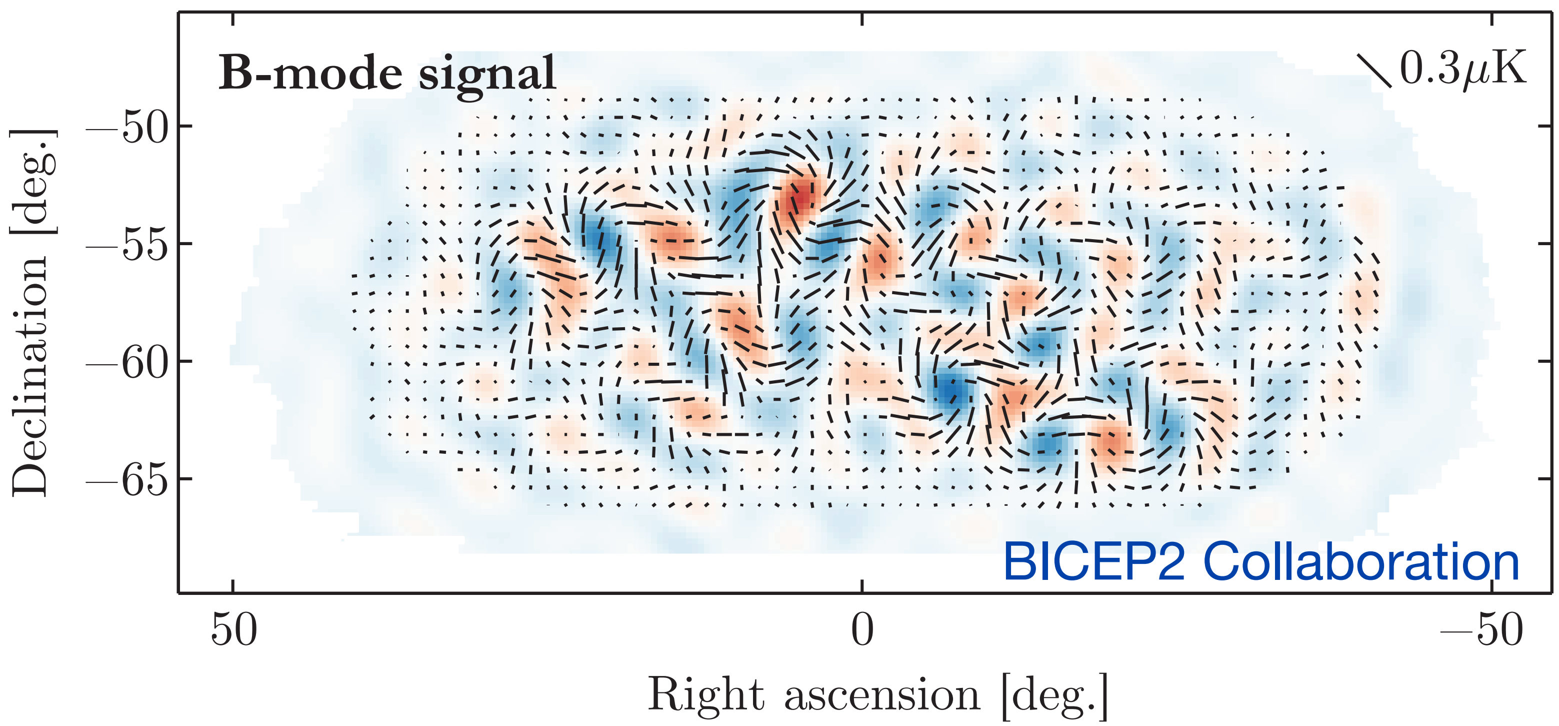
These conditions are sensitive to Planck scale physics:

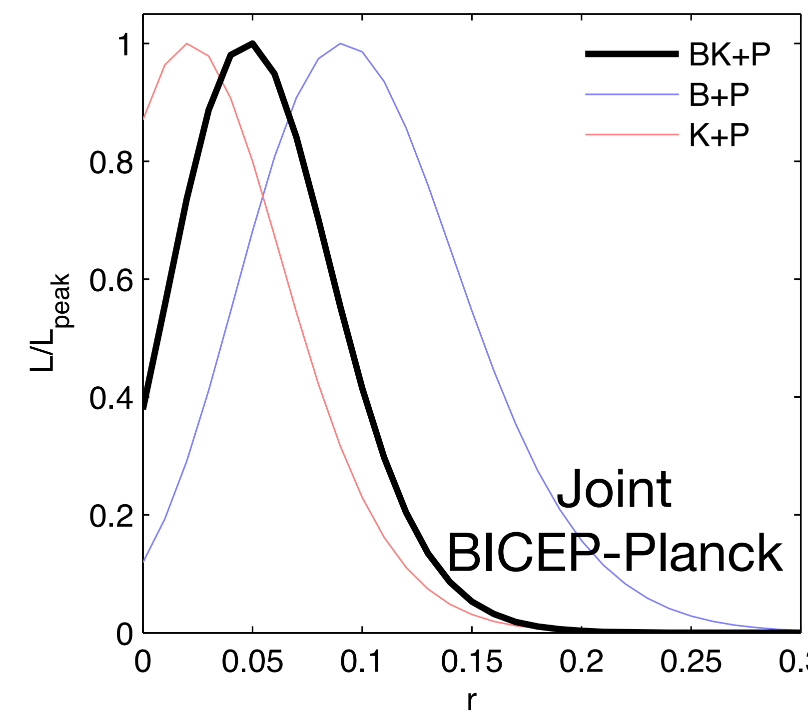
$$\delta V \sim \frac{V}{M_P^2}\phi^2 \quad \Longrightarrow \quad \eta \sim \mathcal{O}(1)$$

This is generic for <u>any</u> model of inflation

Inflation & Gravity Waves

A distinguishing parameter is the tensor-to-scalar ratio r.





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD…
can potentially detect such primordial B-mode if $r \lesssim 10^{-2}$.

LiteBIRD may even have the sensitivity to detect $r \sim 10^{-3}$.

B-mode and Inflation

<u>If</u> primordial B-mode is detected, natural interpretations:

- Inflation took place at an energy scale around the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

- The inflaton field excursion was super-Planckian

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

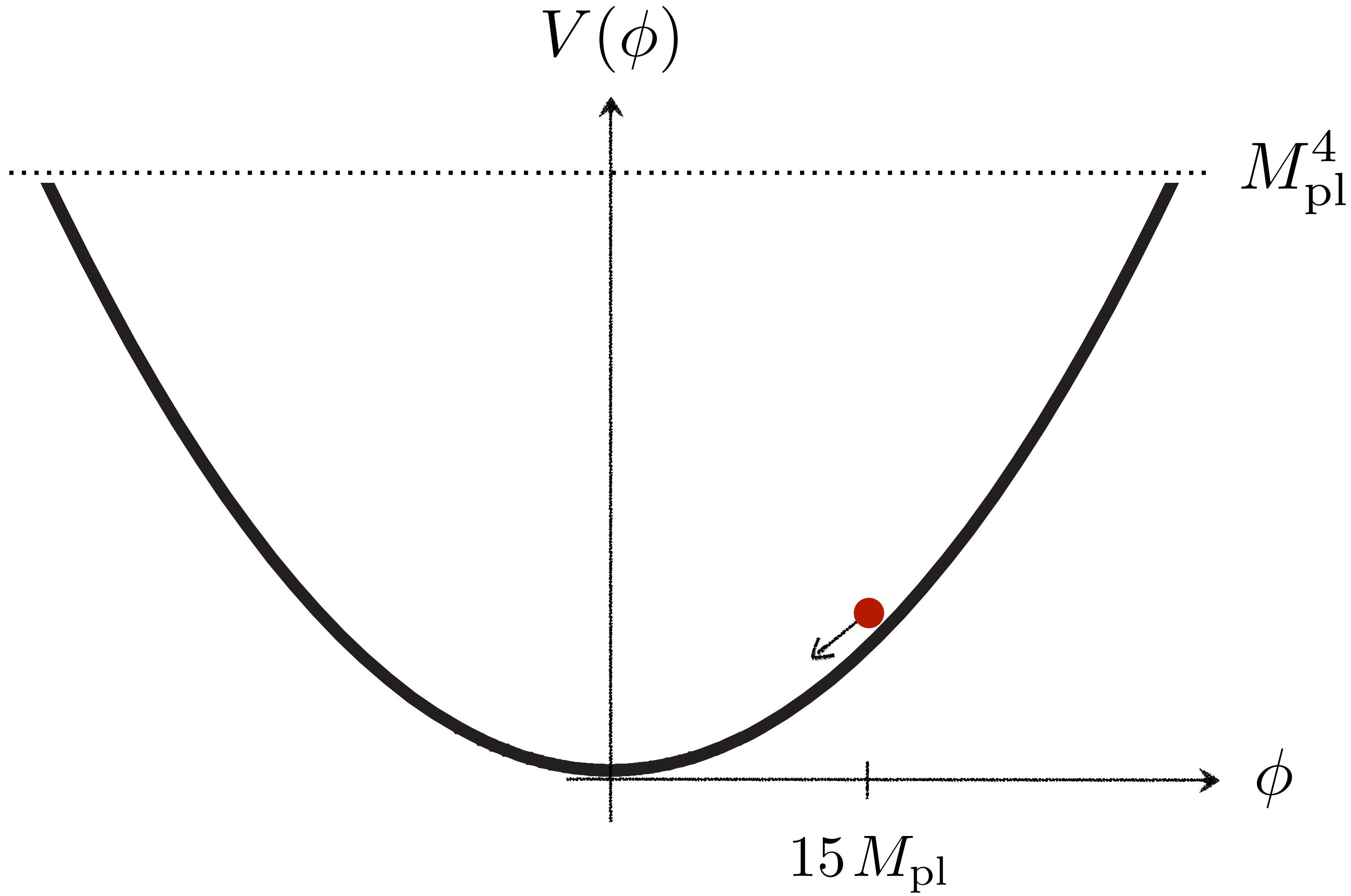
Lyth '96

- Great news for string theory due to strong UV sensitivity!

Large Field Inflation

Chaotic Inflation

Linde '86



Chaotic Inflation

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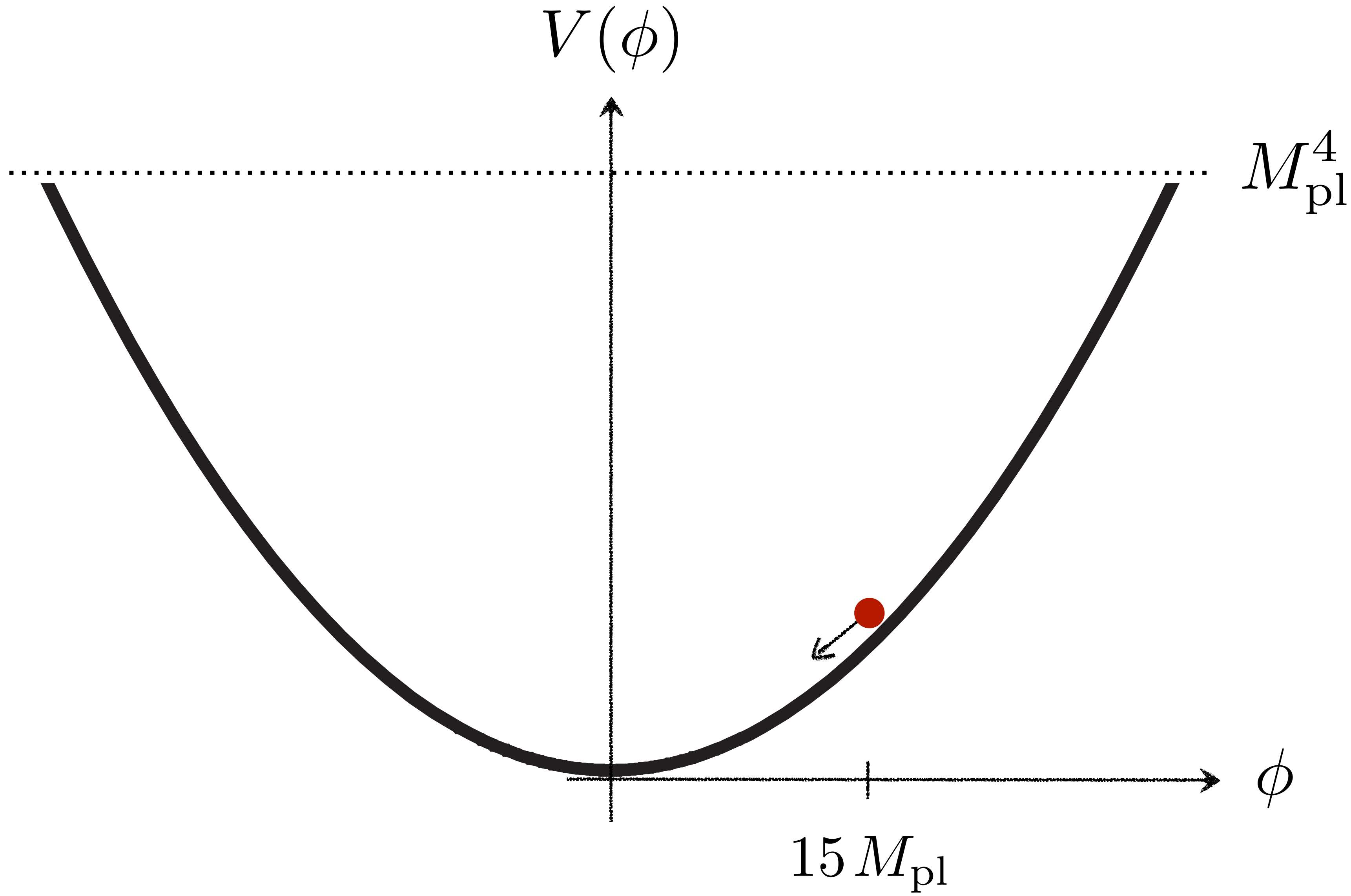
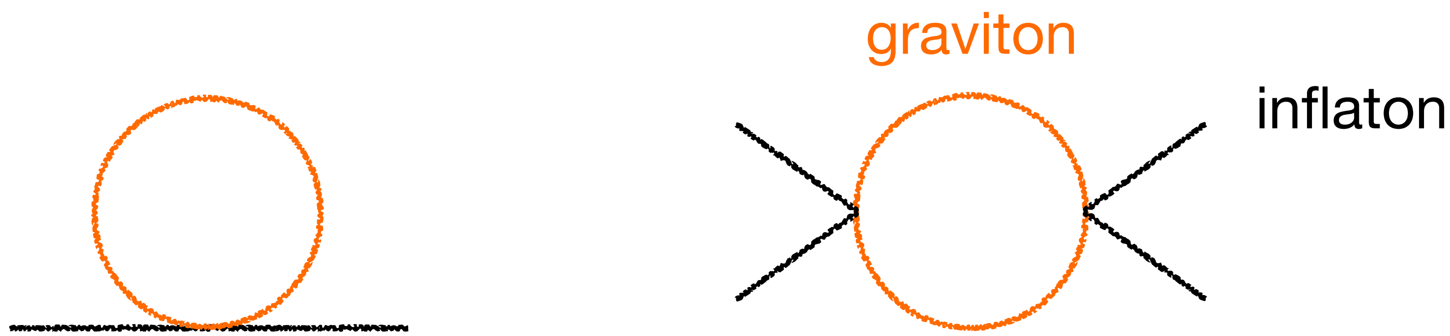


Classical backreaction is under control.

Chaotic Inflation

Linde '86



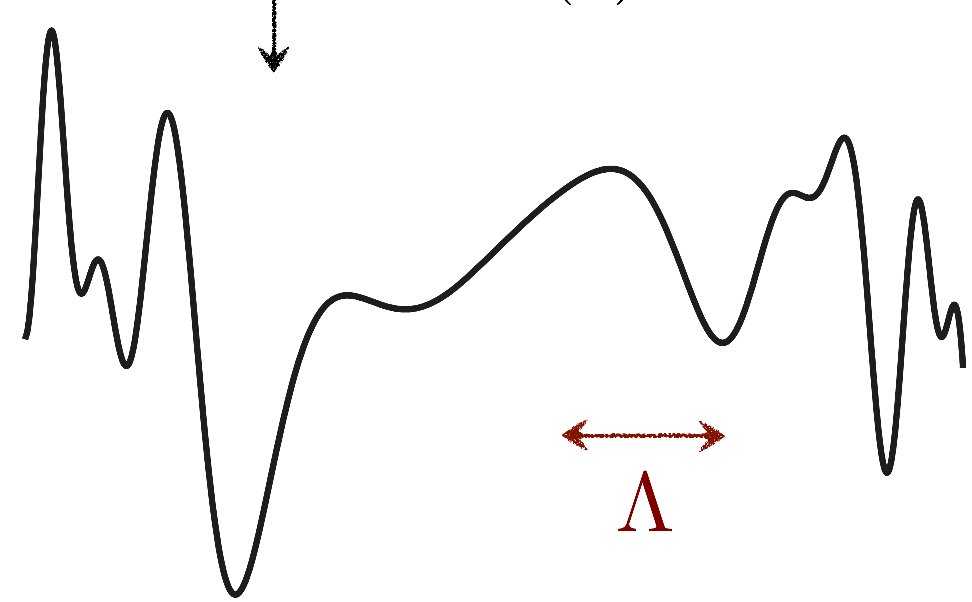
$$\frac{\Delta m^2}{m^2} = c_1 \frac{m^2}{M_{\rm pl}^2} + c_2 \frac{m^2 \phi^2}{M_{\rm pl}^4} \ll 1$$

Quantum corrections are small.

Concerns arise if we consider coupling the theory to the UV degrees of freedom of a putative theory of quantum gravity.

$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

$$\Big\downarrow \; c_i \sim \mathcal{O}(1)$$



Light fields can become heavy;

Heavy fields can become light

Large Field Inflation

- Large field inflation corresponds to models w/ $\Delta\Phi > M_P$

- Chaotic $m^2\phi^2$ inflation **[Linde, '86]** & natural inflation **[Freese et al, '90]** are radiatively stable, but coupling to UV dofs:

- Large field inflation is highly sensitive to UV physics.

Axions & Large field inflation

- Axions seem ideal inflaton candidates: V protected by a perturbatively exact global symmetry:

$$\phi \sim \phi + c \quad \Longrightarrow \quad V^{(p)} = 0$$

Natural Inflation:
Freese et. al ‘90

- Non-perturbative potential:

$$V(\phi) = \sum_k c_k \, e^{-km} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]$$

  - Broken shift symmetry: $\phi \sim \phi + c \quad \longrightarrow \quad \phi + 2\pi f$

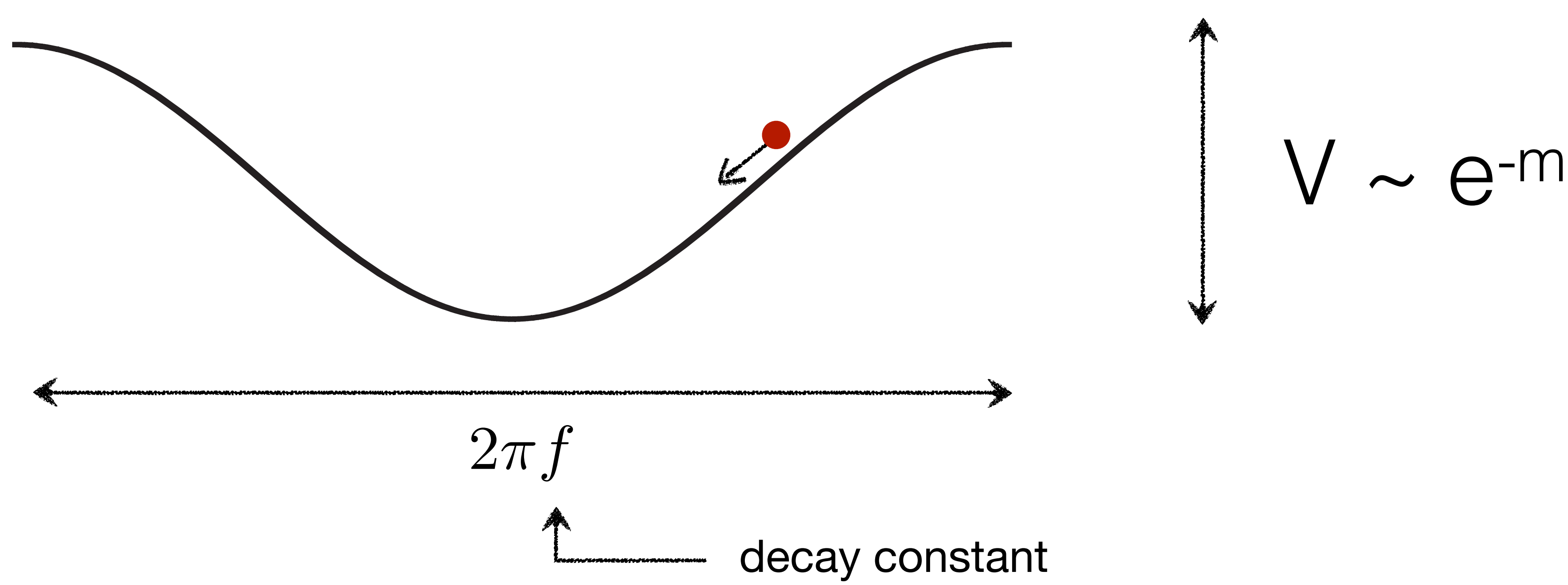
- Controlled, slow-roll potential: $e^{-m} \ll 1 \,, \quad f > M_p$

$$\boxed{f \cdot m > M_p}$$

Axions & Large field inflation

However…

- $f \cdot m \gg M_p$ the global symmetry becomes effectively exact.



- Quantum gravity dislikes and violates global symmetries

Kallosh, Linde, Linde, Susskind '95

Banks, Seiberg '10

Axions in String Theory

String theory has many **higher-dimensional form-fields**:

e.g. $$F = \mathrm{d}A$$

3-form flux (F) 2-form gauge potential: (A)

gauge symmetry: $A \to A + \mathrm{d}\Lambda$

Integrating the 2-form over a 2-cycle gives an **axion**:

$$a(x) \equiv \int_{\Sigma_2} A$$

The gauge symmetry becomes a **shift symmetry**.

Axions & Large field inflation

- Axions are abundant in string compactifications, e.g.

$$b^i = \int_{\Sigma_2^i} B_2 \ , \qquad c^i = \int_{\Sigma_p^i} C_p$$

- Large decay constants do not seem to arise
  - Either $f < M_P$
  - Or higher harmonics become important (and new light states appear)

$$e^{-m} \sim 1$$

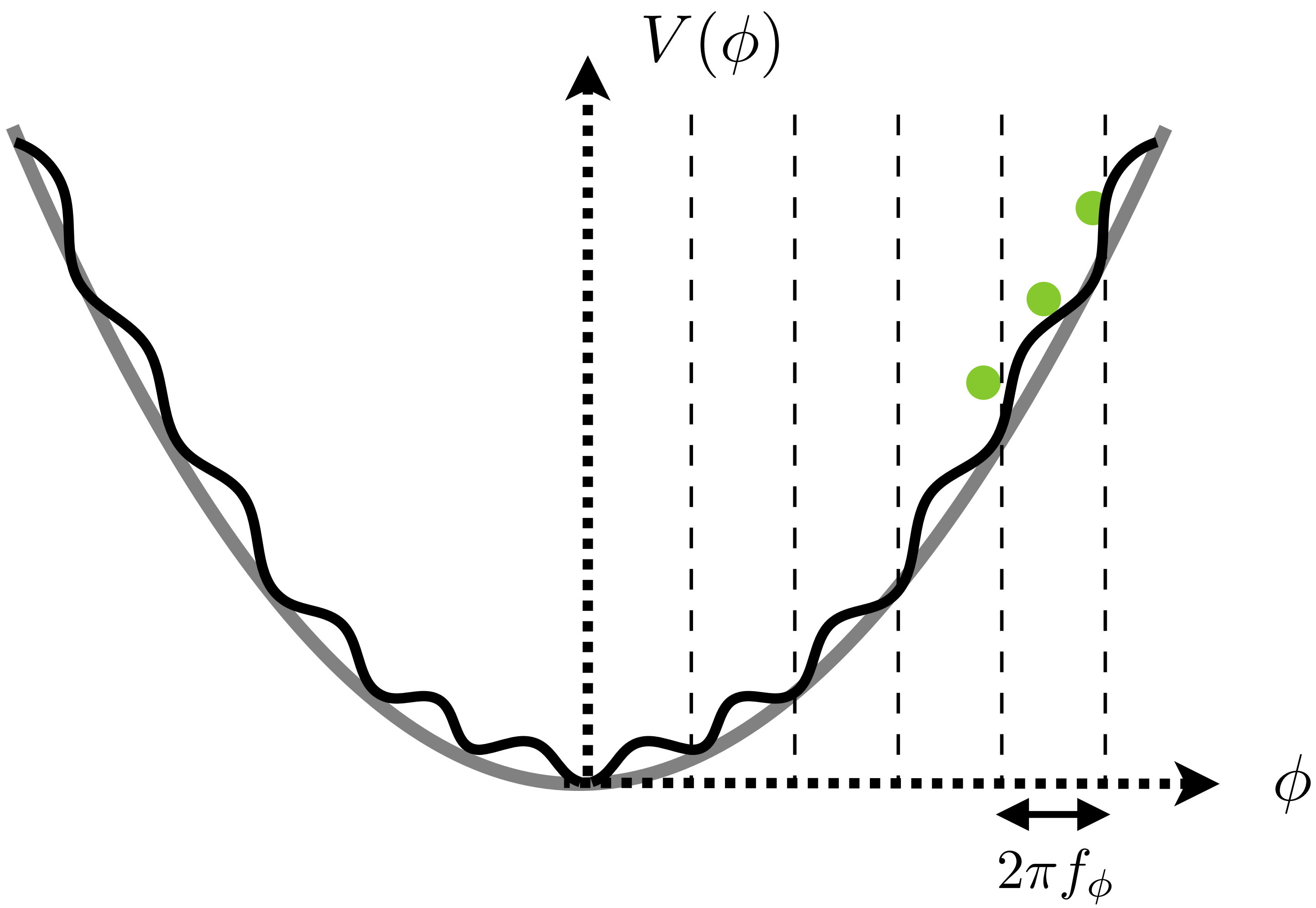
Banks et al. '03
Svrcek, Witten '06

Two Distinct Classes of Large Field Inflation

Multiple Axions

- Alignment [Kim, Nilles, Peloso '04];[Kappl, Krippendorf, Nilles '14]; [Choi, Kim, Yun '14]; [Tye. Wong '14];[Ben-Dayan, Pedro, Westphal '14];[Kappl, Nilles, Winkler '15]; …
- N-flation [Dimopoulos, Kachru,McGreevy,Wacker '05]; ,,,
- Kinetic and Stuckelberg Mixings [GS, Staessens, Ye, '15];[Bachlechner, Long, McAllister, '14-'15]; …
- Multi-field Extra-natural [de la Fuente, Saraswat, Sundrum '14]; …

Axion Monodromy



via brane coupling [Silverstein, Westphal '08];[McAllister, Silverstein, Westphal '08]; ..., or flux potential [Marchesano, GS, Uranga '14];[Blumenhagen, Plauschinn '14]; [Hebecker, Kraus, Witowski, '14];[McAllister, Silverstein, Westphal, Wrase '14]; ...

A single axion with a *perturbative* mass

Multi-Axion Inflation

Multi-axion Inflation

- Recent efforts into evading such constraints with

Multiple Axions

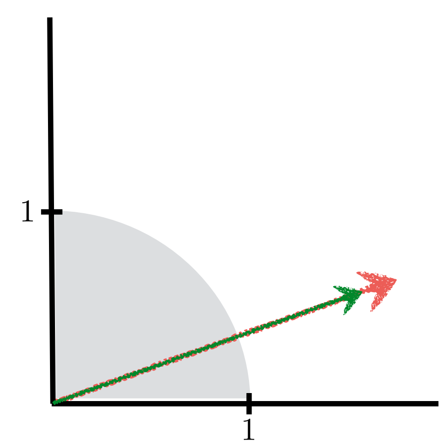
- Aligned axions: $\phi\,,\ \rho$

KNP '04; ...

$$V(\phi,\rho) = \Lambda_1\left[1-\cos\left(\frac{\phi}{f_1}+\frac{\rho}{g_1}\right)\right]+\Lambda_2\left[1-\cos\left(\frac{\phi}{f_2}+\frac{\rho}{g_2}\right)\right]$$

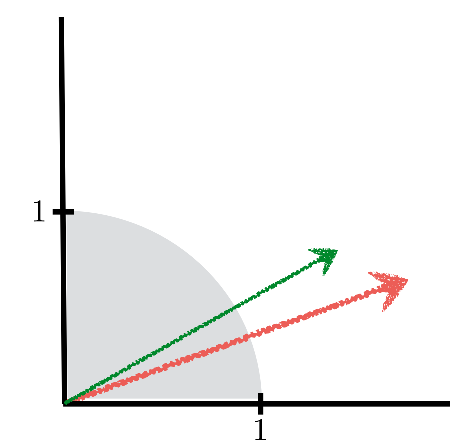
$$f_1/g_1 = f_2/g_2$$
$$f_\perp \to \infty$$

$$f_1/g_1 \approx f_2/g_2$$
$$f_\perp \gg M_P$$



$$\vec{z}_1 = \begin{pmatrix} 1/f_1 & 1/g_1 \end{pmatrix}$$

$$\vec{z}_2 = \begin{pmatrix} 1/f_2 & 1/g_2 \end{pmatrix}$$



Multi-axion Inflation

- Recent efforts into evading such constraints with

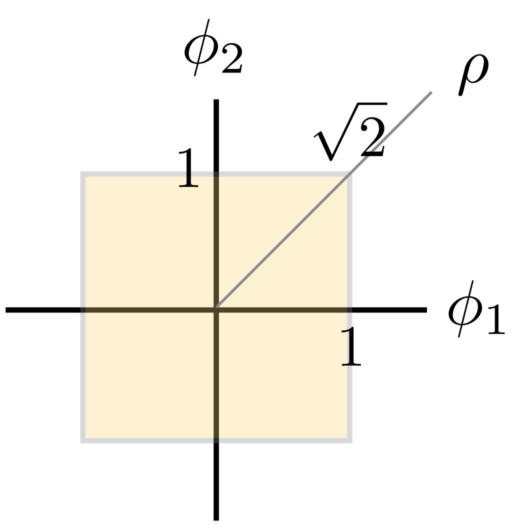
Multiple Axions

- N-flation: N axions ϕ_i Dimopoulos et al. '08

$$V(\phi_i) = \sum_i \Lambda_i \left[1 - \cos\left(\frac{\phi_i}{f}\right)\right]$$

- Large decay constant along the "radial" direction:

$$\rho^2 = \sum_i \phi_i^2 \qquad f_\rho^{(eff)} \sim \sqrt{N} f$$



Multi-axion Inflation

- Recent efforts into evading such constraints with

Multiple Axions

- Generically: large-N, KNP-alignment, kinetic mixing

$$(\Delta\rho)_{max} \sim \begin{cases} N^p f\,, & p \geq 1/2 \\ n^N f \end{cases}$$

Choi et al. ’14
Bachlechner et. al ’14
Junghans ‘15

- Even if $f \ll M_p$, it seems possible that $(\Delta\rho)_{max} \gg M_p$

Axions & Large Field Inflation

- Is there a fundamental reason why models with a single axion have small decay constants?

$$m \cdot f < M_P$$

- If so, can multi-axion models (or axion monodromy) evade it?

- Input from quantum gravity & string theory needed

The
Weak Gravity Conjecture

The Weak Gravity Conjecture

Arkani-Hamed et al. '06

- The conjecture:

"Gravity is the Weakest Force"

- For every long range gauge field there exists a particle of charge q and mass m, s.t.

$$\frac{q}{m} M_P \geq \text{``1''}$$

$M_P \equiv 1$

The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

$M_P \equiv 1$

The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

- Form bound states

$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

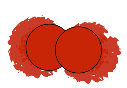
- All these (BH) states are stable. Trouble w/ remnants Susskind '95

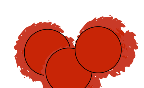
$M_P \equiv 1$

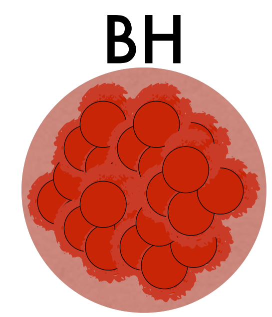
The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

  - Form bound states







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  - All these (BH) states are stable. Trouble w/ remnants $\quad$ Susskind '95

- Need a light state into which they can decay

$$\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

The Weak Gravity Conjecture

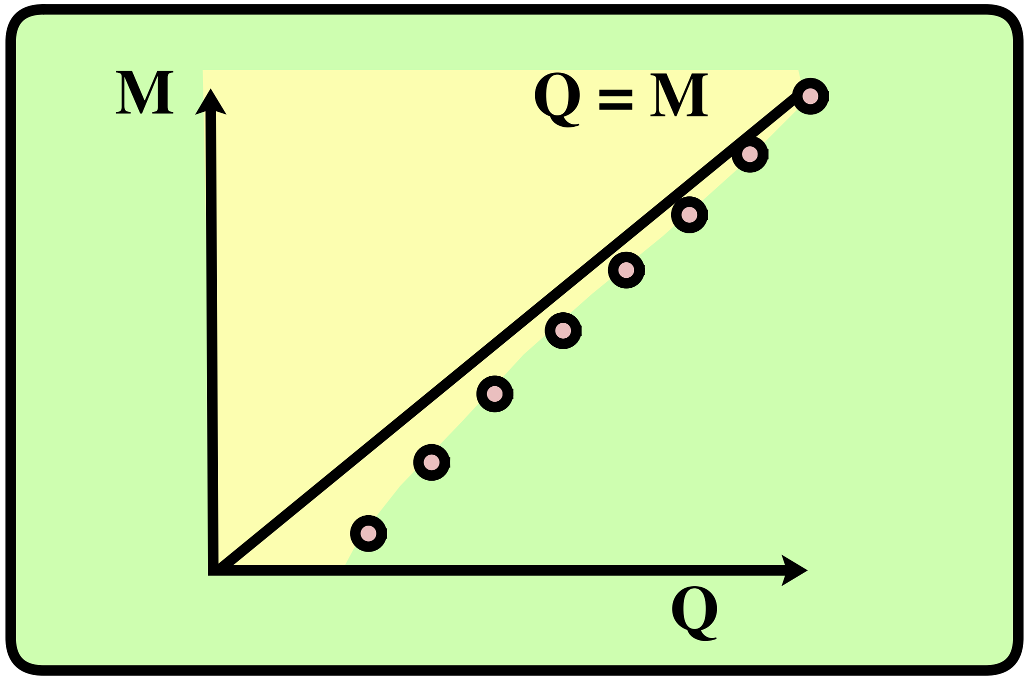
Arkani-Hamed et al. '06

- For bound states to decay, there must ∃ a particle w/

$$\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

Strong-WGC: satisfied by <u>*lightest*</u> charged particle

Weak-WGC: satisfied by <u>*any*</u> charged particle



E.g. Heterotic spectrum:

$$M^2 \propto Q_L^2 + 2N_L - 2$$

The Weak Gravity Conjecture

- Suggested generalization to p-dimensional objects charged under (p+1)-forms:

$$\frac{Q}{T_p} \geq \text{“}1\text{”}$$

- p=-1 applies to instantons coupled to axions:

$$e^{-S_{inst}} = e^{-m+i\phi/f} \qquad \Longrightarrow \qquad fm \leq \text{“}1\text{”}$$

  - Seems to explain difficulties in finding $f > M_P$

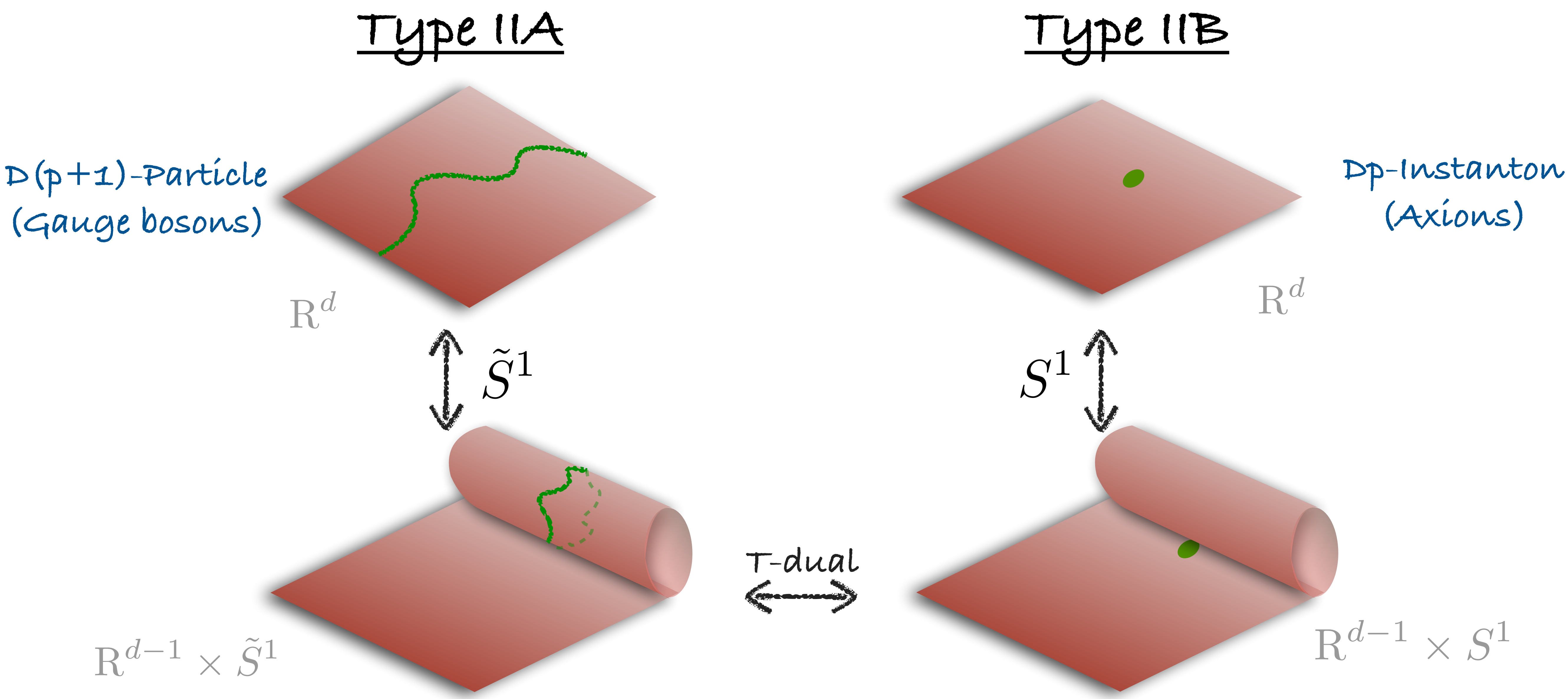
- Is there evidence for the p=-1 version of the WGC?

Brown, Cottrell, GS, Soler

WGC and Axions

Brown, Cottrell, GS, Soler

- T-duality provides a subtle connection between instantons and particles



WGC and Axions

Brown, Cottrell, GS, Soler

Type IIA

Gauge fields: $A_i \sim \int_{\Sigma_2^{(i)}} C_3$

Particles: D2 on $\Sigma_2^{(i)}$

WGC

$$\tilde{m}_k = m_k \frac{\sqrt{g_{33}}}{2\pi\, l_s}$$

$$\tilde{q}_k^i = (f_k^i)^{-1} \frac{\sqrt{2}}{4\pi\, l_s}$$

“Couplings”:

$$\tilde{g}_s = \frac{g_s}{\sqrt{g_{33}}}$$

$$\tilde{M}_P = M_P \sqrt{g_{33}}$$

Type IIB

Axions: $\phi_i \sim \int_{\Sigma_2^{(i)}} C_2$

Instantons: D1 on $\Sigma_2^{(i)}$

$$S_{inst_k} \sim -m_k + i(f_k^i)^{-1}\phi_i$$

“Couplings”:

$$g_s$$

$$M_P$$

WGC and Axions

Brown, Cottrell, GS, Soler

4d Type IIB D1-instantons	4d Type IIA D2-particles	5d M-theory M2-particles
m_i	$\tilde{m}_i \sim m_i$	$M_i^{(5d)} \sim m_i$
f_i	$\tilde{q}_i \sim f_i^{-1}$	$Q_i^{(5d)} \sim f_i^{-1}$
$g_s \ll 1$	$\tilde{g}_s \gg 1$	$R_M \to \infty$

- Apply the WGC to 5d particles:

$$\boldsymbol{\frac{Q^{(5d)}}{M_i^{(5d)}} M_P^{(5d)}} = \boldsymbol{\frac{M_P^{(IIB)}}{\sqrt{2} f_i\, m_i}} \geq \text{“}\mathbf{1}\text{”} \equiv \left(\frac{Q}{M} M_P \right)_{\mathrm{Ext}_{5d}} = \sqrt{\frac{2}{3}}$$

WGC and Axions

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WGC and Axions

- For each axion (gauge U(1)) there must be an instanton (particle) with

$$e^{-S_{inst}} = e^{-m+i\phi/f}$$

$$\boxed{f \cdot m \leq \frac{\sqrt{3}}{2} M_P}$$

Brown, Cottrell, GS, Soler

For a RR 2-form in IIB string theory. Similar bounds for axions from other p-forms in other string theories have also been obtained.

Multiple Axions/ Multiple U(1)'s

WGC and Axions

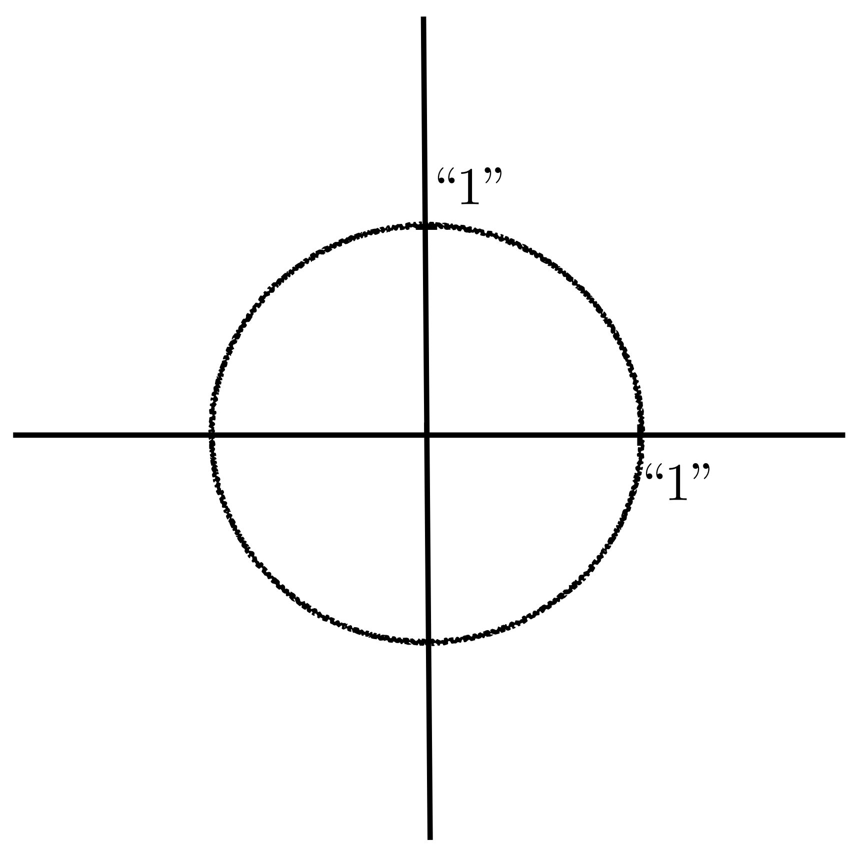
Brown, Cottrell, GS, Soler '15
Cheung, Remmen '14
Rudelius '15

Multiple axions/U(1)s

- Consider two U(1) bosons (axions): there must be 2 particles (instantons) i=1,2, so that BH's can decay.

$$\vec{z}_i \equiv \frac{M_P}{M_i}\begin{pmatrix} Q_i^1 & Q_i^2 \end{pmatrix} \qquad \left(= \frac{M_P}{\sqrt{2}\, m_i}\begin{pmatrix} 1/f_i^1 & 1/f_i^2 \end{pmatrix} \right)$$

$$|\vec{z}_{EBH}| \equiv \text{“}1\text{”}$$



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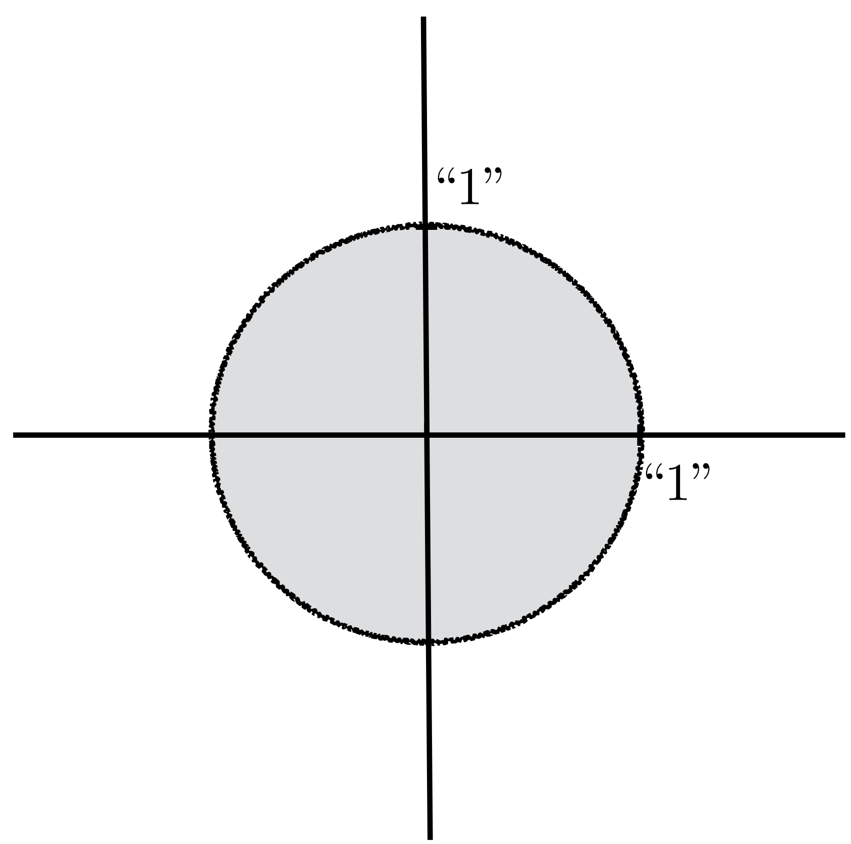

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$$\vec{z}_{p1} \geq (\text{“1”} \quad 0)$$

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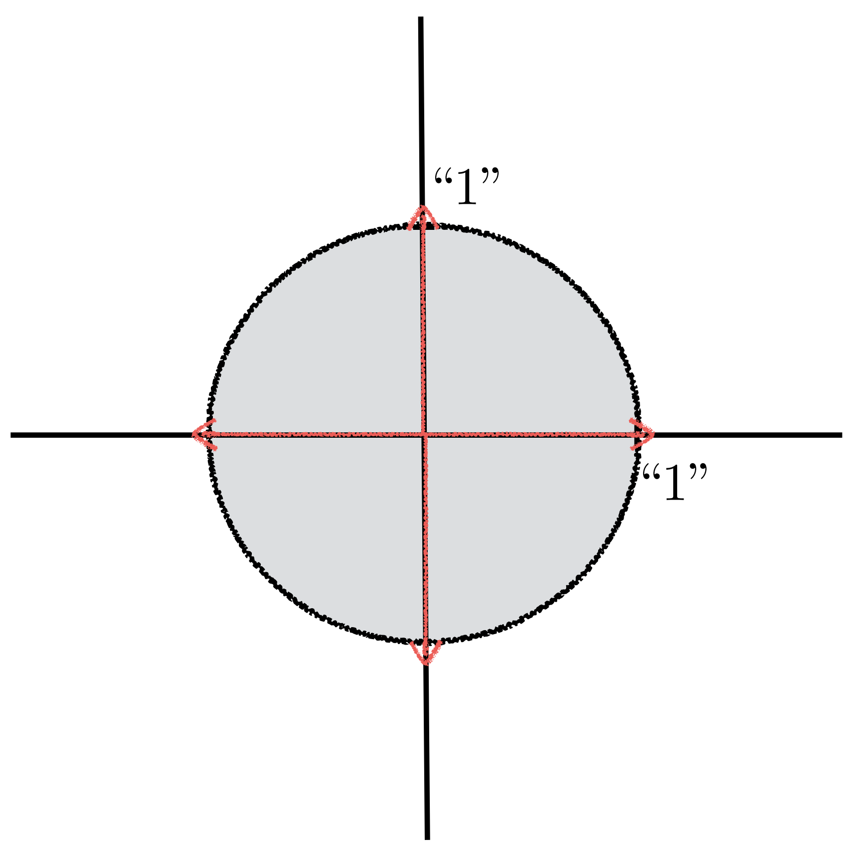

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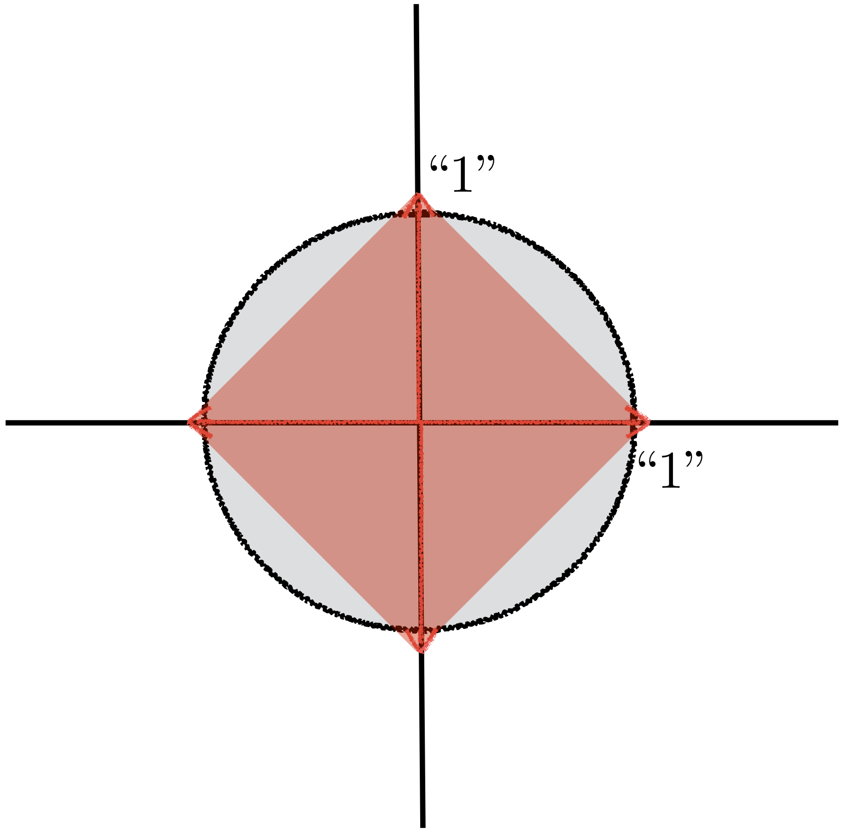

WGC

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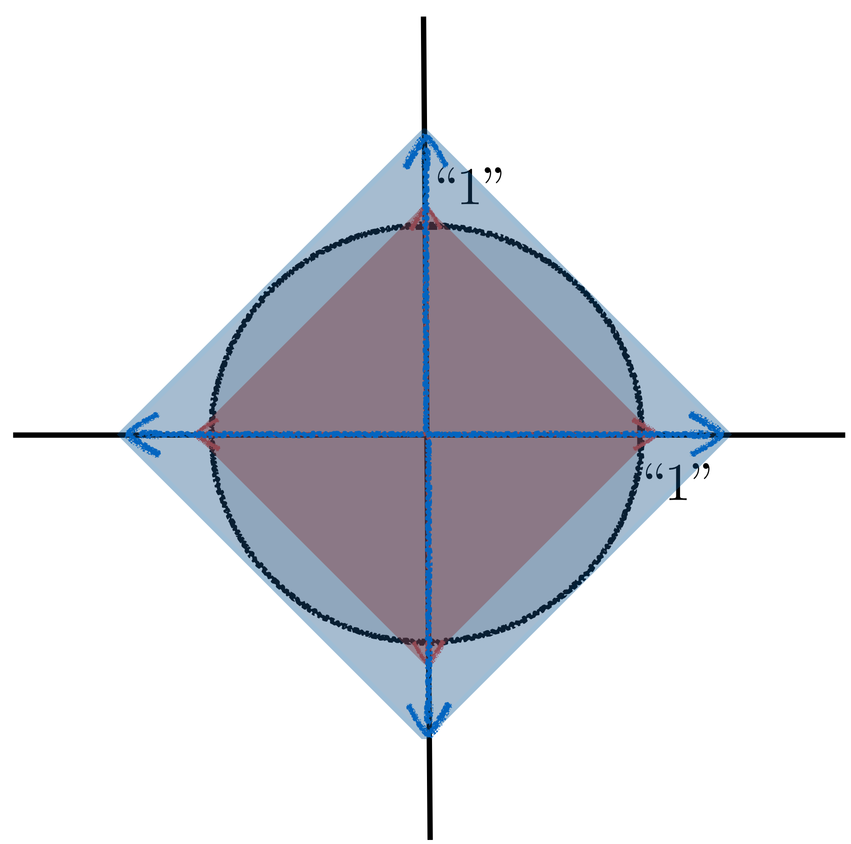

WGC

$$\vec{z}_{p1} \geq \left(\text{“}1\text{”}\sqrt{2} \quad 0 \right)$$

$$\vec{z}_{p2} \geq \left(0 \quad \text{“}1\text{”}\sqrt{2} \right)$$

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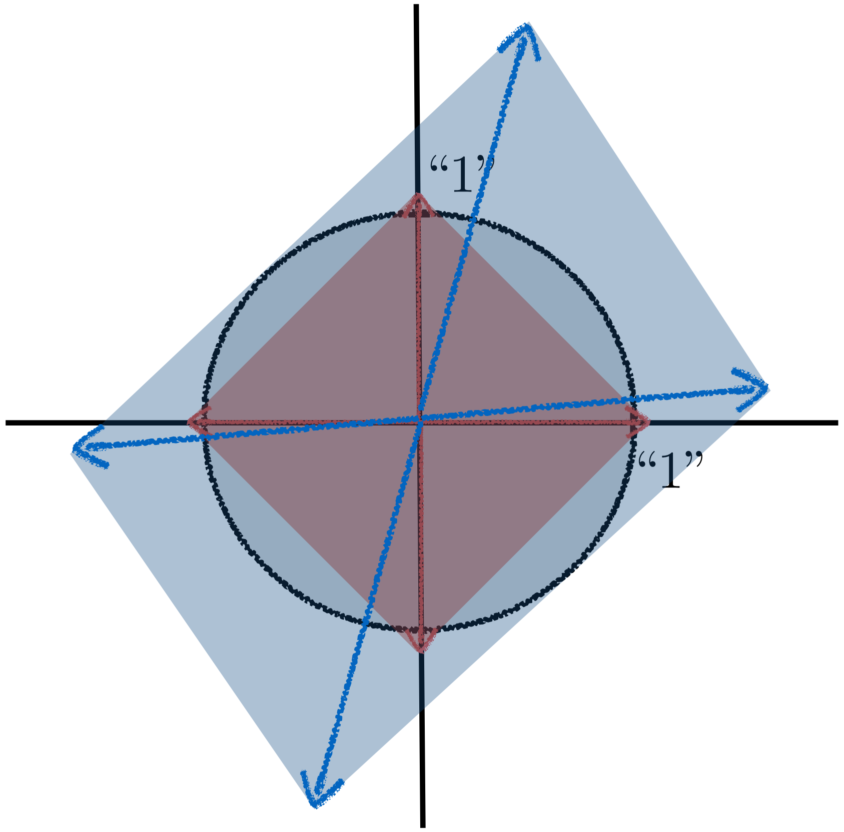

WGC

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$$\vec{z}_{p2} \geq \left(0 \quad \text{“1”}\sqrt{2} \right)$$

WGC and Axions

Multiple axions/U(1)s

Brown, Cottrell, GS, Soler '15
Cheung, Remmen '14
Rudelius '15

- Consider two U(1) bosons (axions): there must be 2 particles (instantons) i=1,2, so that BH's can decay.

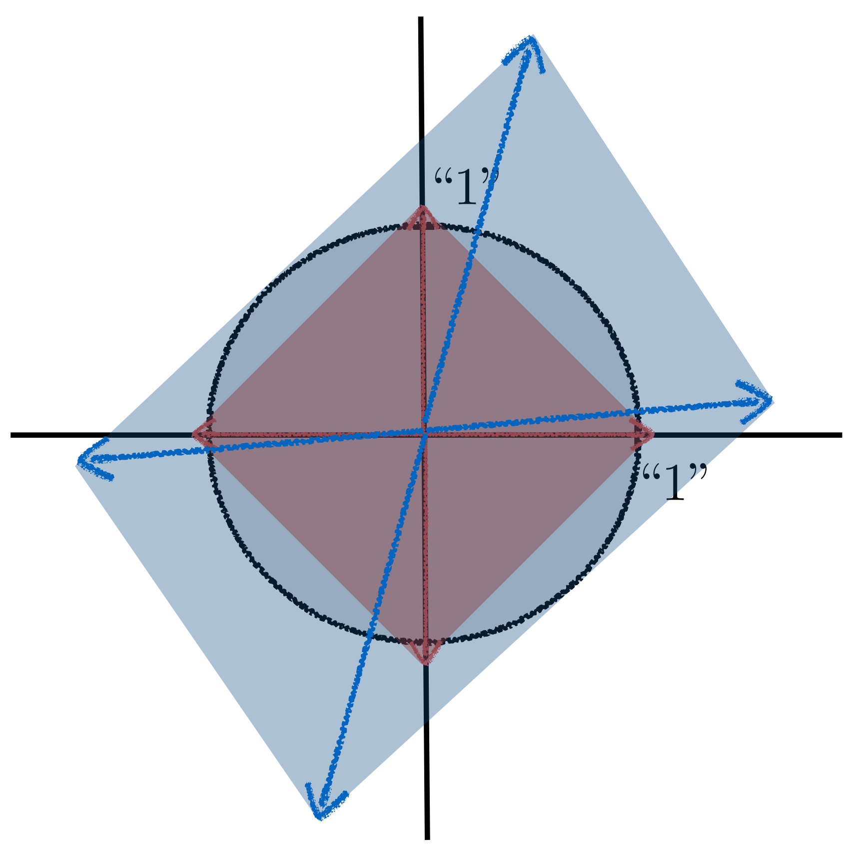
$$\vec{z}_i \equiv \frac{M_P}{M_i}\left(Q_i^1 \quad Q_i^2 \right) \qquad \left(= \frac{M_P}{\sqrt{2}\, m_i}\left(1/f_i^1 \quad 1/f_i^2 \right)\right)$$

$$|\vec{z}_{EBH}| \equiv \text{“1”}$$

$$|\vec{z}_{BH}| \leq \text{“1”}$$

$$\vec{z}_{p1} \geq (\text{“1”} \quad 0)$$

$$\vec{z}_{p2} \geq (0 \quad \text{“1”})$$



WGC

$$|\vec{z}| = \text{“1”}$$

$$\cap$$

$$\text{Convex Hull}\,\{\vec{z}_{p1}, \vec{z}_{p2}\}$$

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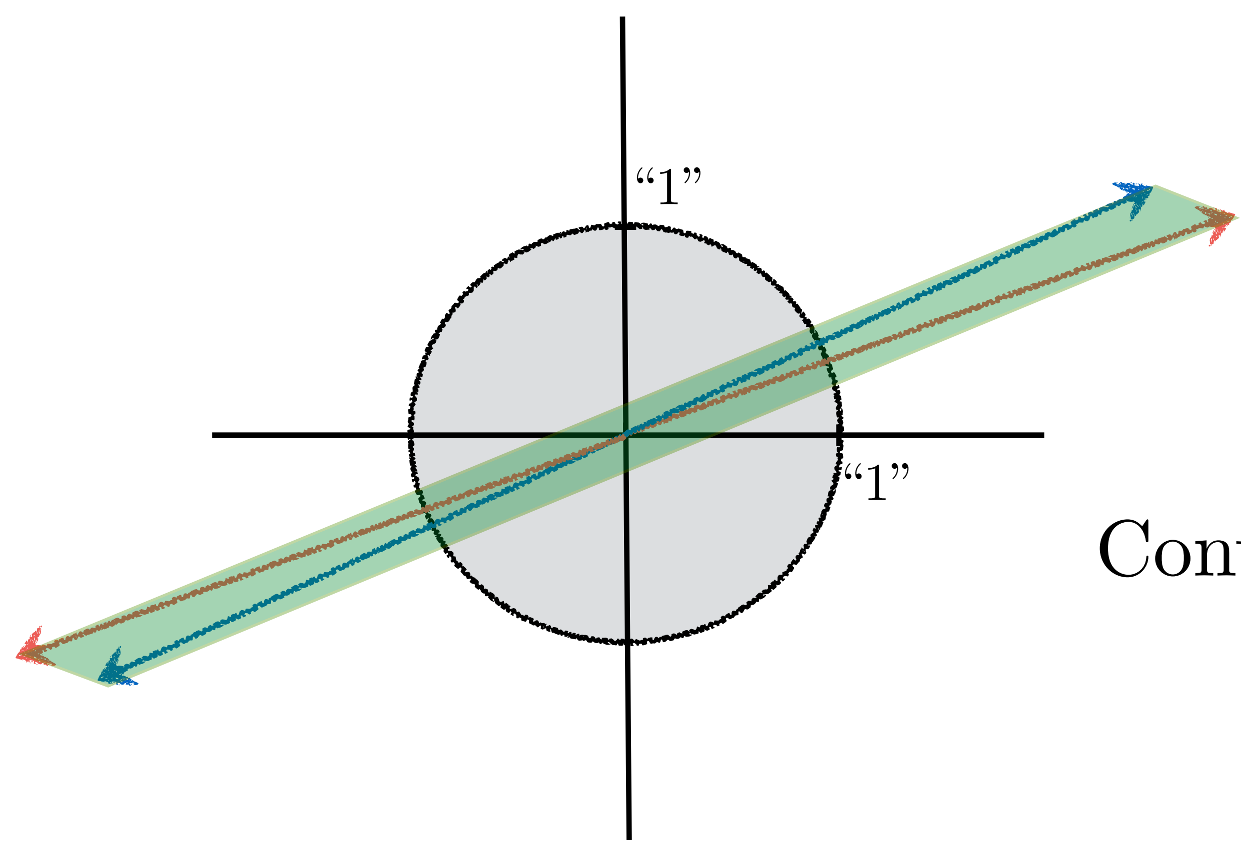
KNP



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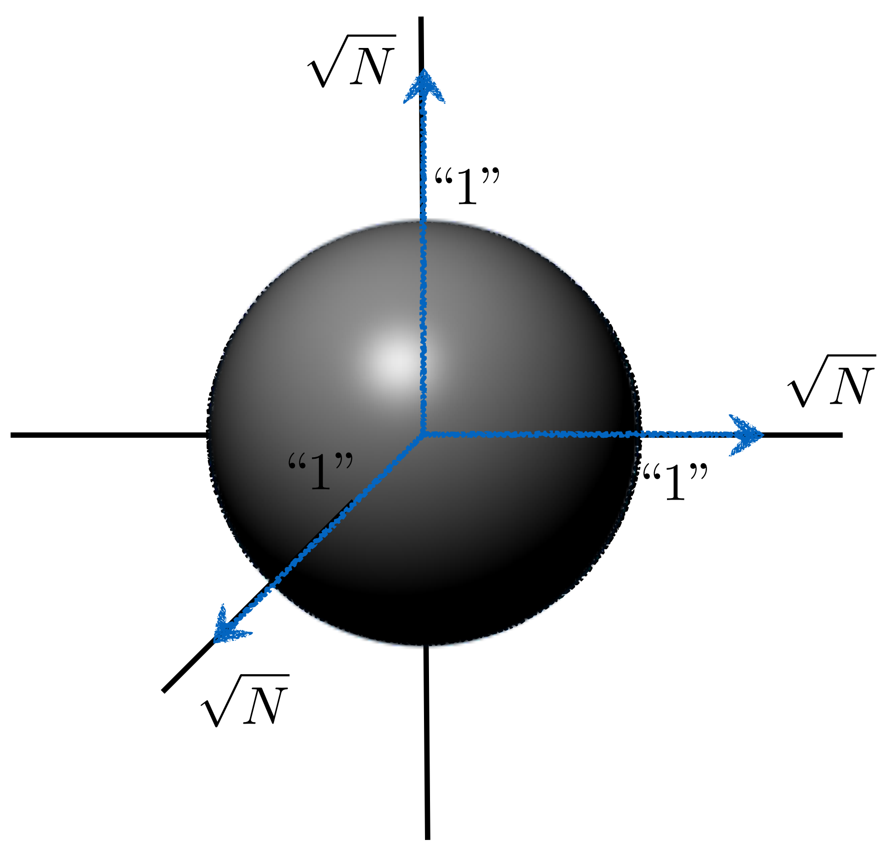
N-flation

$$z_i^k \geq \sqrt{N}\delta_i^k$$



WGC

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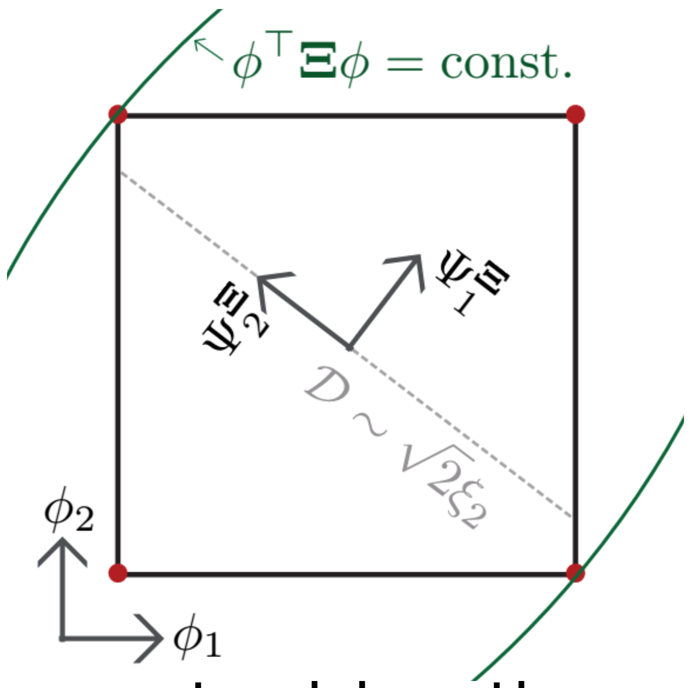
$$\cap$$
$$\text{Convex Hull}\,\{\vec{z}_{p1}, \vec{z}_{p2}\}$$

WGC and Multi-axion Inflation

- Generally, given a set of instantons that gives a super-Planckian ``diameter" in axion field space:

$$\mathcal{L} = \frac{1}{2}\partial\boldsymbol{\phi}^{\top}\boldsymbol{\Xi}\,\partial\boldsymbol{\phi} - \sum_{i=1}^{N}\Lambda_i^4\left[1-\cos\left(\phi_i\right)\right]$$



we showed that the convex hull generated by these instantons ***does not*** contain the extremal ball.

- Our conclusions agree w/ the gravitational instanton diagnostics of [Montero, Uranga, Valenzuela '15]

Is there a way around this?

Loophole suggested in Brown, Cottrell, GS, Soler,
“Fencing in the Swampland”, arXiv:1503.04783 [hep-th]

A possible loophole

- The WGC requires f·m<1 for ONE instanton, but not ALL

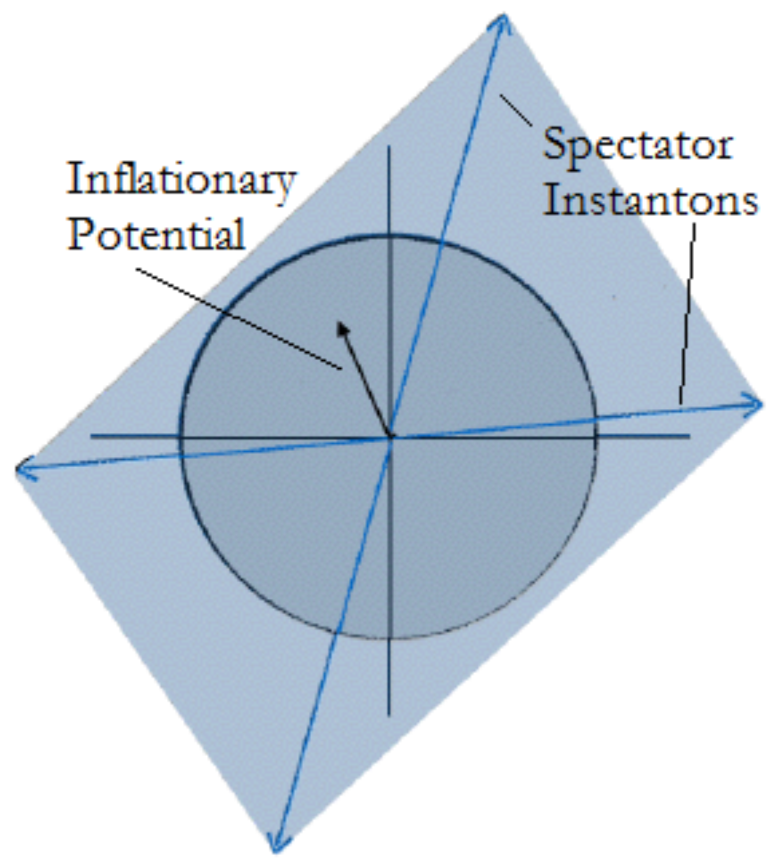
$$V = e^{-m}\left[1-\cos\left(\frac{\Phi}{F}\right)\right] + e^{-M}\left[1-\cos\left(\frac{\Phi}{f}\right)\right]$$

With $\quad 1 < m \ll M, \qquad F \gg M_P > f, \qquad M \times f \ll 1$

- The second instanton fulfills the WGC, but is negligible, an "spectator". Inflation is governed by the first term.

A possible loophole

- In the presence of “spectator” (negligible) instantons that fulfill the WGC, dominant instantons can generate an inflationary potential



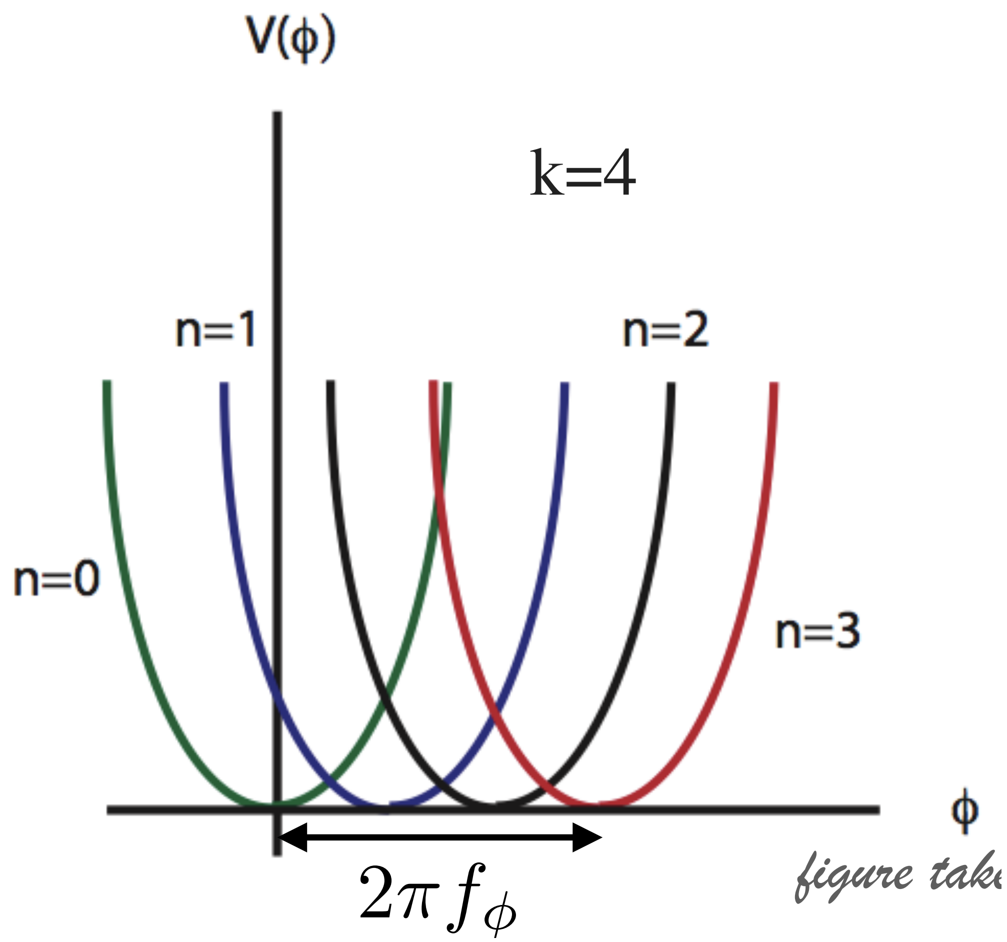
- These scenarios generically violate the Strong-WGC: “The LIGHTEST charged states satisfy $Q/M > 1$“

WGC: Weak vs Strong

- Infinitely manly stable remnants in a finite mass range leads to pathologies. Susskind
- This led one to *conjecture*: [Arkani-Hamed, Motl, Nicolas, Vafa '06]
  - there shouldn't be ∞ *exactly stable remnants* **(weak)**
  - these ∞ *remnants can decay to lightest state* **(strong)**
- The loophole we found amounts to hiding our ignorance about the spectrum of states at the Planck scale.
- The whole point of large field inflation in string theory is to tame the UV sensitivity.
- Burden of proof is on those who claim to have found viable string theory realizations.

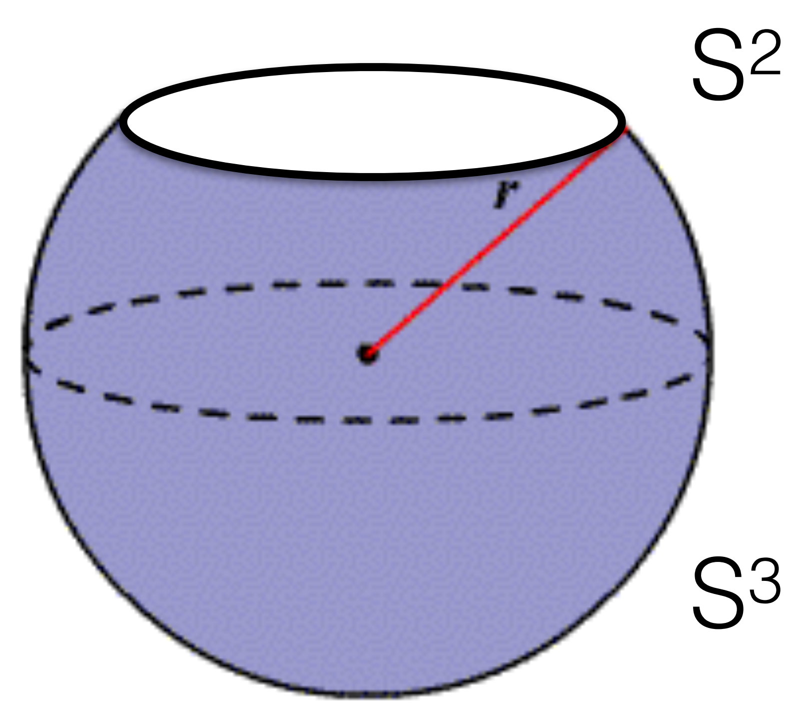
Axion Monodromy

- Axion is mapped to a ***massive*** gauge field.
- Possible tunneling to different branches of the potential:



e.g.

D7 on M^6



k D5 on 3-cycle

- Suppressing this tunneling can lead to a bound on field range (hence r)

Brown, Garcia-Etxebarria, Marchesano, GS, in progress

Extra-Natural Inflation

Arkani-Hamed, Cheng, Creminelli, Randall

- 5D U(1) gauge theory compactified on a circle:

$$\delta V(\phi) = \frac{3(-1)^S}{4\pi^2} \frac{1}{(2\pi R)^4} \sum_{n\in\mathbb{Z}} c_n e^{-2\pi n R m_5} \,\mathrm{Re}\, e^{in\phi/f}$$

$$c_n(2\pi R m_5) = \frac{(2\pi R m_5)^2}{3n^3} + \frac{2\pi R m_5}{n^4} + \frac{1}{n^5},$$

  - KK 1-loop potential, interpreted as instanton sum
  - WGC $\Rightarrow$ $2\pi R\, m_5 \cdot f \leq 1$

- Give up parametric control, rely on n^{-5} suppression?

$$f = \frac{1}{2\pi R\, g_5} \gg 1 \; ; \qquad R \cdot m_5 \ll 1$$

Extra-Natural Inflation

- f ~ 1/Rg >> 1 seems to clash w/ the “magnetic” WGC:

$$M_{mag} \sim \Lambda/g^2 \qquad\qquad \Longrightarrow \quad \frac{M_{mag}}{Q_{mag}} \leq M_p \Leftrightarrow \Lambda \leq g M_p \ll 1/R$$
$$Q_{mag} \sim 1/g$$

- Suggestion: use KNP alignment de la Fuente, Saraswat, Sundrum
  - Use two U(1)’s w/ particles of charges (1,0) & (N,1)

$$V = V_0 \left[1 - \cos\frac{A}{f_A}\right] + \tilde{V}_0 \left[1 - \cos\left(\frac{NA}{f_A} + \frac{B}{f_B}\right)\right]$$

  - If N >>1, then f_{eff} ~ N f_B without taking $f_{A/B}$ >> M_P

- String coupling in the regime of interest as gN ~ 1?
- Assumptions on magnetic spectrum & UV completion

Extra-Natural Inflation

- Is this potential reliable over super-Planckian ranges?

$$V(\phi) \approx \Lambda^4 \sum_n \frac{e^{-nm}}{n^5}\left[1-\cos\left(\frac{n\phi}{f}\right)\right]$$

- $V(\phi)$ is obtained by integrating over a field slice with frozen metric, gauge fields and internal radius.

$$e^{-iV(\phi)} \overset{?}{\sim} \int [d\psi][d\phi'] e^{iS(\psi,\phi+\phi',A_\mu=0,R=R_0,g_{\mu\nu}=\delta_{\mu\nu})}$$

- Dynamics of the dilaton (radius) and gravity not taken into account. Instanton interpretation is obscure.

- "KK sum ~ instanton sum" reminiscent of what was found in an N=2 SUSY context [e.g., Nekrasov, …].

Work in Progress

Conclusions

Conclusions

- Inflation is sensitive to UV physics. Large field inflation requires *even more input* from quantum gravity.
- We have made the WGC precise for (a large class of) axions which can be dualized to U(1) gauge fields.
- Constraints on multiple axions in terms of convex hull (bound on the “diameter” of axion space):
  - KNP, N-flation, kinetic mixing,…

Conclusions

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- Profound connections to quantum gravity promise to illuminate black holes, inflation, and string theory.

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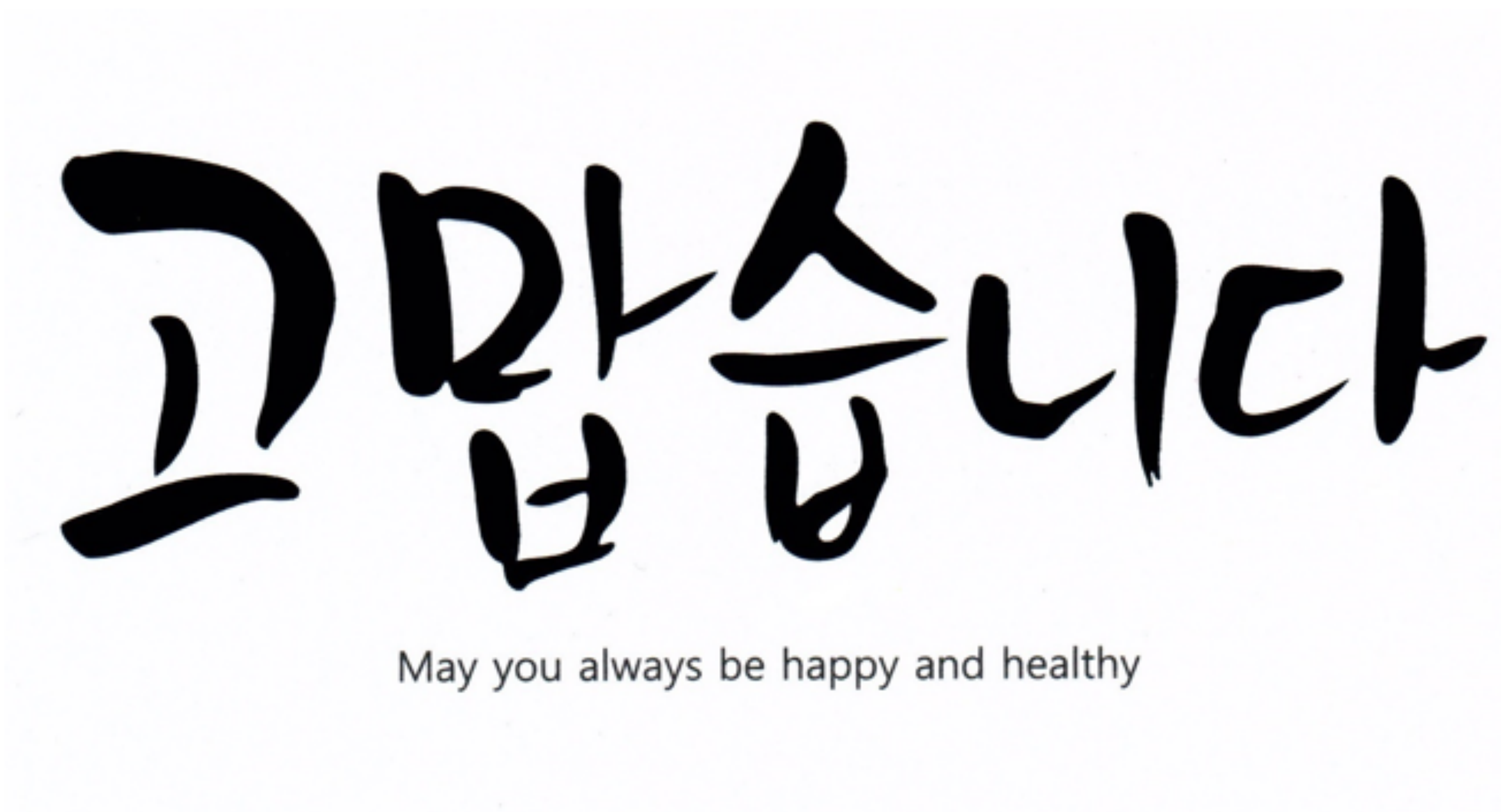

Backup Slides

Example?

- Stabilized compactification of IIB orientifold [Denef et al '05]
    - Orientifold of resolution of $T^6/Z_2 \times Z_2$
    - $h^{1,1} = 51$, 48 exceptional divisors, $SO(8)^{12}$ on O7's
    - Stabilizing complex structure moduli w/ fluxes and Kahler moduli w/ instantons to an AdS minimum:

$$W = W_0 + \sum_i A_i e^{-q^i{}_j T^j}$$

$\Rightarrow$ Vol $_{\text{Einstein}} \simeq 55$; Vol $_{\text{String}} \simeq 7$

- Recently used for RMT study of multi-axion inflation [Bachlehner et al '14]; "diameter" $D \simeq 1.1\, M_P$ (so $f < M_P$ still).
- Many possible corrections: α' and G_3-flux corrections to W, K as well as to M_P.